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A learning progression based teaching module on the causes of seasons

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Summary. — In this paper, we report about designing and validating a teaching learning module based on a learning progression and focused on the causes of seasons. An initial learning progression about the Celestial Motion big idea —causes of seasons, lunar and solar eclipse and Moon phases— was developed and validated. Existing curricula, research studies on alternative conceptions about these phenomena, and students' answers to an open questionnaire were the starting point to develop initial learning progressions; then, a two-tier multiple-choice questionnaire was designed to validate and improve it. The questionnaire was submitted to about 300 secondary-school students whose answers were used to revise the hypothesized learning progressions. This improved version of the learning progression was used to design a module focused on the causes of seasons in which students were engaged in quantitative measurements with a photovoltaic panel to explain changes of the Sun rays' flow on the Earth's surface over the year. The efficacy of our module in improving students' understanding of the phenomenon of the seasons was tested using our questionnaire as pre- and post-test.

1. – Introduction

Research in science education has extensively proved that students experience many difficulties in explaining the change of seasons [1-5]. The majority of them provide incorrect explanations ranging from the naive idea that when the Earth is closer to Sun it is summer, to more sophisticated, but still incorrect, ideas that the Earth's axis flips back and forth during its motion around the Sun. A correct understanding of the seasons' phenomenon from a physics viewpoint requires students to combine the properties of light, Gauss' flux law and energy transfer. Furthermore, students should develop the ability to connect two-dimensional representations to three-dimensional models. Teaching about change of seasons gives students also the opportunity to discuss about global warming and climate changes, a relevant socio-scientific issue [6], using physics-based arguments as the factors affecting the temperature at a given location on the Earth or the mechanisms underlying energy transfers between radiation and environment. However, qualitative activities are often not effective in addressing students' intuitive ideas, since the physical mechanisms behind this phenomenon remain often hidden [7,8]. To address this issue we developed an inquiry-based module about the change of seasons using a learning progression approach. The research questions that guided the study were:

RQ1 Which is the learning progression that best describes the development of students' understanding about the causes of seasons?

RQ2 To what extent a teaching-learning module developed from the learning progression is effective in addressing students' misconceptions about the causes of seasons?

2. – Theoretical framework

A learning progression describes how students build up their understanding of a given topic starting from a naive to a correct, scientific idea. In particular, learning progressions are descriptions of the successively more sophisticated representation of a given phenomenon that can follow one another as children learn about and investigate a topic over a broad span of time [9]. Learning progressions are centred around big ideas, namely cross-cutting concepts that help students connect different phenomena, empirical laws, and explanatory models. Typically, a learning progression features a sequence of levels described by specific progress indicators, which refer to what students know at each level. Validation of a learning progression is a cyclical process: an initial learning progression is first developed from the existing literature or from a didactic reduction of the chosen big idea; a measurement instrument is then constructed or adapted and data are collected to inspect the alignment between the levels of the learning progression and the actual students' achievements. If the alignment is poor, the measurement instrument and the initial learning progression need to be revised. The cycle ends when alignment between actual and hypothesized outcomes becomes sufficiently satisfactory [10]. Different methodologies have been adopted by researchers to validate learning progressions. Some authors [10] constructed a multiple-choice questionnaire as a measurement instrument and used Rasch analysis to compare students' achievements across different school levels with the hypothesized learning progression. Other authors [11] used qualitative data as interviews and written artifacts to validate and revise a learning progression about genetics. In our research study, we adopted the first approach. Learning progressions about astronomical phenomena and causes of seasons were developed in [12-14]. However, these studies are mostly focused on middle-school level (11–13 years old) and do not address underlying physics mechanisms. For such reasons, we designed a learning progression to describe students' understanding of the phenomenon across secondary school (14–18 years old).

3. – Methods

3˙1. *Research instrument and analysis.* – To answer RQ1 we developed an initial learning progression about causes of seasons based on research studies in astronomy education, Italian secondary-school science curriculum, and answers to an open questionnaire administered to 189 secondary-school students. See table I for details.

To evaluate the alignment between our learning progression and the actual students' achievements, we developed a two-tier questionnaire with 12 multiple-choice questions

Table I. – *Initial learning progression.*

Phenomenon	Progression level	Questionnaire Item	Progress indicator: The students know that
Season	1	Q5–Q8	Seasons are due to the inclination of solar rays that changes during the year
	2	Q1–Q4	Level 1 + the revolution of Earth around the Sun
	3	Q9–Q12	Level 2 + tilt of Earth's axis
	Upper anchor	Q13–Q16	Level 3 + Earth's axis constant direction in space

and 36 true-false statements. The first tier featured three true-false statements concerning simple facts that students need to link together to build up the explanation required in the multiple-choice question. To facilitate questionnaire submission in secondary school, we included also questions about Moon phases and eclipses. Therefore, only 12 true-false statements and 4 multiple-choice items (Q1–Q16) were about change of seasons. The questionnaire items were designed in such a way to establish a connection with the hypothesized learning progression levels. For the sake of clarity, we report in this paper only the analysis of the students' answers to these items. Students' answers were analysed using Rasch analysis [15-17]. Rasch analysis relates the probability of correctly answering an item to the difference between a student's ability and an item's difficulty. Results are usually displayed through a Wright map, in which students' abilities and items' difficulties are presented together. Given the adopted design of the questionnaire items, comparing difficulties of the items hence allows to compare also the levels of the hypothesized learning progression and to revise them according to actual students' achievements. To answer RQ2, drawing from the revised learning progression levels, we developed a sets of teaching activities and implemented the module with secondary-school students. Effectiveness of the designed activities was investigated using the same questionnaire. Given the limited size of the sample in the implementation of the modules, we analyzed only the frequency of students' correct answers.

3˙2. *Sample.* – To validate the learning progression, the questionnaire was submitted to 300 Italian secondary-school students at the beginning (14 years old) and at the end of secondary school (18 years old). All students in our sample had already studied the targeted topics using only curriculum-based materials as required by the Italian National Curriculum Indications. One hour was given to complete the questionnaire in an anonymous form. To validate the effectiveness of the module, we implemented the activities with 45 secondary-school students (two fifth classes, 17–18 years old) for a total of 12 hours for each implementation.

4. – Results

4˙1. *Analysis of students' answers to the questionnaire.* – Out of the 300 collected questionnaires, only 254 were analyzed: 114 by first class students, 140 by fifth class students. The remaining 46 questionnaires were left out because they missed information about the class attended by the students. The Wright map of the questionnaire is

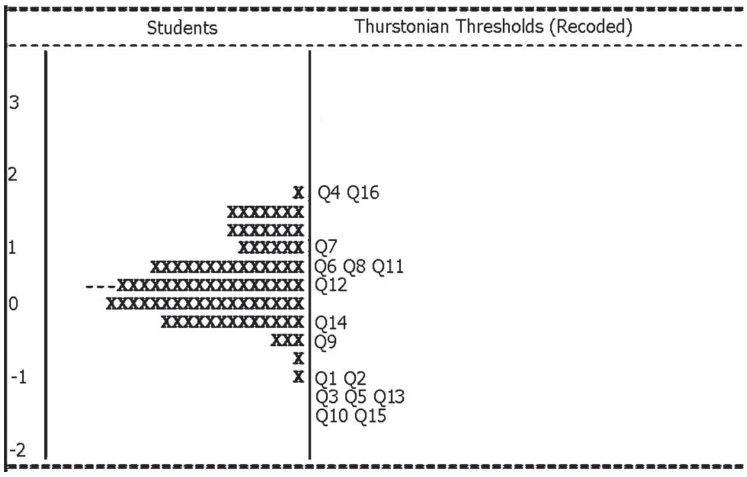

Fig. 1. – Wright map of the questionnaire used in the study.

reported in fig. 1. Each x represents 3 students, each row is 0.255 logits. The map suggests that each student's abilities are well distributed over the range of question difficulties. The average ability estimate is 0.44 logits. Since the average ability is greater than average items' difficulty (set to 0), the questionnaire was suitable for the students of the sample.

The analysis of the items' difficulties shows that only about 40% of the low-ability students correctly think that the Sun-Earth distance does not influence seasons' change, while, as expected, this percentage increases up to 80% for high-ability students. On the contrary, the percentage of high-ability students who think that the inclination of Earth's axis does not change during the year is not significantly higher than the corresponding percentage of low-ability students. This result suggests that students may correctly claim that the tilt of the axis influences seasons' change but may have many difficulties when they try to relate the energy received by Earth and the different conditions under which solar light hits Earth's surface [18]. Hence, Rasch analysis does not confirm the hypothesized level sequence of the learning progression. While items related to distance misconception were the easiest to answer, as expected, the items related to axis variable-tilt misconception and to the role of the revolution motion along the orbit were amongst the most difficult items. Hence, we modified and refined the hypothesized learning progression about seasons' change, as reported in table II. For the sake of coherence, we changed also the progress indicators formulation. Our findings suggest that the most difficult concept for the students to grasp in understanding the mechanism underlying change of seasons is to bring together the notion of the tilted axis with its constant direction in space and Earth's revolution around the Sun.

4˙2. *Module development.* – In this section we describe the teaching activities we developed from the analysis of students' answers to the questionnaire. Since the role of the Earth's axis on the change of seasons was the most difficult to understand for the students, we chose to focus on the relationships between the energy received by the Earth and the different conditions under which Solar light hits the Earth's surface. In particular, to give students a basic idea of the main physical mechanism underlying the

TABLE II. – *Revised learning progression.*

Phenomenon	Progression level	Progress indicator: The students know that
Season	1	Seasons are due to Earth's axis inclination w.r.t. the orbit's plane
	2	Level 1 + the inclination of solar rays changes during the year
	3	Level 2 + constant direction in space of Earth's axis
	Upper anchor	Level 3 + revolution of Earth around the Sun and constant tilt of Earth's axis w.r.t. the orbit's plane

cause of seasons, we focused on radiation flow and energy transfers. The main aim is to guide students to understand the mathematical relationships between the flow across a surface and: i) the angle between the normal to the surface and the direction of the incident radiation (cosine law); ii) the distance between the surface and a point-like source (inverse square distance law). The cosine law is a model of how sun rays flow varies at a fixed time of the year over the entire Earth surface leaning towards the Sun; and at a fixed place on the surface as the Earth completes its revolution around the Sun. Similarly, the inverse square distance law is a model of the variations of sun rays flow as the distance between the Earth and the Sun changes. Comparing the predictions of the two models, one easily obtains that the tilt of the Earth's axis is predominant with respect to the small eccentricity of the Earth's orbit in the explanation of the change of seasons. Particular emphasis is put on involving students in discussions, since the beginning, about what would happen if the axis of the Earth was not inclined but perpendicular to the orbit and if the distance between Earth and Sun was constant. The module activities provide students also with evidence about the relevance of further factors that affect a given region climate. The aim is to discuss the influence of the daylight duration and to elicit the role of water and soil on the environment temperature. The activities proposed in the module are summarized in table III.

4˙3. *Module evaluation.* – The analysis of the students' answers to the questionnaire items about change of seasons is reported in fig. 2. Item 1 groups Q1–Q4 questions, item 2 groups Q5–Q8 questions, and so on. The most difficult items in the pre-test concerned the role of constant direction in space of the Earth's axis on the change of seasons (item 4, 6% of correct answers) and the role of the environment on the temperature at a given location on the Earth (item 2, about 12% of correct answers). The tilt of the axis and Earth's revolutionary motion around the Sun seem the two factors the students were most familiar with for explaining the cause of seasons (about 20% of correct answers in the corresponding items). It is worth noting that even if students had already addressed these topic in their school curriculum, the varying distance between the Sun and the Earth and the changing direction of the Earth's axis emerged in about 40% of the answers as possible factors for the change of seasons. Not surprisingly, the idea that the axis of Earth changes direction in space during the orbital motion emerged in about 20% of the answers. Analysis of the post-test answers shows that students improved their performance in all items, especially in item 4 (about 80% of correct answers). Such evidence suggests that the module activities focused on the relationships between the

Table III. – *Overview of the teaching module "Causes of seasons".*

Activity	Time (hours)	What students do	Intended objectives	Teaching materials
1	2	Discuss about the possible factors underlying the cause of seasons. Design an experiment to show the relevance of the identified factors.	To elicit students' ideas about the change of seasons. To reinforce students' skills in selecting control variables in experiments.	Worksheet 1: Why we experience different seasons
2	3	Measure the output power of a photovoltaic panel illuminated by an incandescent lamp when changing the source- panel distance and the inclination of the panel with respect to the direction of the incoming radiation.	To introduce the cosine and inverse square laws of the incident radiation flow on a surface. To reinforce students' skills in dealing with analysis and fitting methods.	Worksheet 2: How the Earth's axis inclination and the distance between the Earth and Sun affect seasons' change
3	2	Estimate the solar radiation flow at different locations of the Earth at a fixed time of the year and at a fixed location of the Earth over the year using the models constructed in the previous activity. Estimate the radiation flow at perihelion and aphelion.	To exploit mathematical models to describe experimental evidences.	Worksheet 3: What influences more between distance and axis inclination
4	3	Measure the specific heat of the sand. Discuss about the role of the environment on the temperature of a given location on Earth's surface.	To relate the temperature of a location to the heat transfers between radiation and the environment.	Worksheet 4: Why the sand burns during summer

constant direction in space of the Earth's axis and the changing radiation flow on Earth's surface were effective in helping the students to develop an informed view of the causes of seasons and in addressing the Sun-Earth distance misconception.

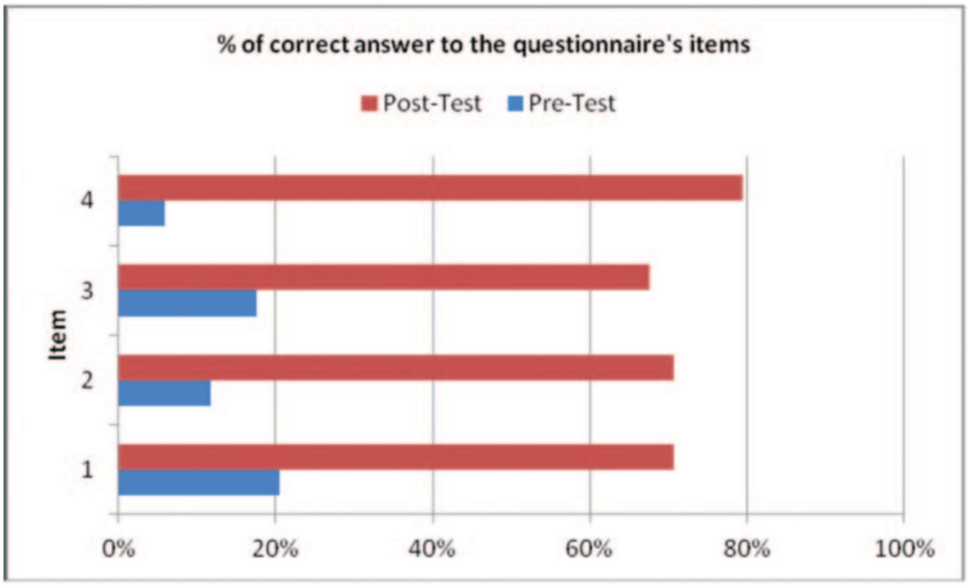

Fig. 2. – Distribution of students' correct answers for the four items in the pre- and post-test written questionnaire. Refer to table II for items' description.

5. – Discussion and Conclusions

Concerning the first research question, consistently with most of the previous studies, the average percentage of correct answers at the end of secondary school does not exceed 60%. However, our results suggest also that students' conceptions about change of seasons improve with instruction. Plausibly, the students of the fifth classes in our sample were exposed to quantitative approaches about this phenomenon; in particular they learned some of the underlying physics mechanisms. To this end, we note that the initial envisioned progression was only partially supported by data. In particular, we expected that students would have related the change of inclination of solar rays first to the revolution of Earth and then to the tilt of Earth's axis and finally to the axis' constant direction in space. However, this progression was not supported by students' answers to the questionnaire, resulting in a progression that relates the seasons change first to the axis tilt and then combines this notion with the changing positions of Earth along its orbit. A plausible explanation may be that to recognize how sunlight flux on Earth's surface changes when Earth is moving along the orbit requires a reasoning which involves at the same time physics and geometrical considerations. Concerning the second research question, the main implication of the above results concerns the teaching of the change of seasons. To give students a basic idea of the main physics mechanism underlying the phenomenon, we designed a module focused on two key ideas: radiation flow and energy transfer. In particular, experimental activities are proposed with the aim to show the relevance of the Earth's axis tilt with respect to the small eccentricity of the Earth's orbit on the change of seasons and to investigate basic aspects of the energy transfers between the radiation and the substances (soil, water, rocks) present in the environment in a given location. To this concern, given the complexity of the topic, however, we aimed at simply showing that the energy transfer mainly depends on the environment composition, making students think about the impact of astronomical and physical phenomena on everyday life. Overall, the results of the analysis of students' answers to the pre- and post-test questionnaires are encouraging and support the effectiveness of the proposed activities. In particular, the distance misconception and the naive idea that the Earth axis may change direction in space seem to have been successfully addressed. We plan to improve the module by exploiting online simulations about the incident radiation flow during the motion of the Earth along its orbit.

Appendix

Questionnaire

State whether each of the following statements is true or false

Q1 The Sun produces more energy during summer than during winter

Q2 When a surface is lighted up by a light source, the energy absorbed by the surface is maximum when light hits the surface perpendicularly

Q3 Solar rays' incidence on the Earth's surface changes during the year

Q4 The main factor for which summer and winter alternate is (please tick the correct one):

1. The distance between Sun and Earth changes during the year, so the incidence of solar rays on the Earth's surface varies
2. The inclination of the Earth's axis with respect to the orbit plane changes during the year, therefore the incidence of the solar rays on the Earth surface varies
3. Earth's axis direction in space changes during the year therefore the incidence of the solar rays on the Earth's surface varies
4. Earth's position along its orbit changes during the year, therefore the incidence of the solar rays on the Earth's surface varies

State whether each of the following statements is true or false

Q5 Earth's surface absorbs energy from the Sun

Q6 In a certain place of the Earth the temperature depends on energy transfers with the environment

Q7 In a certain place of the Earth the absorbed energy depends on the atmosphere's thickness

Q8 The reason for which in Italy during summer it is hotter than in winter is that during summer (please tick the correct one):

1. the Earth is closer to the Sun and the day lasts more than in winter
2. the inclination of the Earth's axis changes
3. solar rays are less inclined and the day is longer
4. the Sun produces more energy

State whether each of the following statements is true or false

Q9 Earth's axis precesses during the year

Q10 Earth's axis is inclined with respect to the Earth's orbit plane

Q11 Earth's axis remains parallel to itself during the year

Q12 Some students answer to the question: "What causes the changes in the inclination of solar rays on the Earth surface during the year?" with the following answers. Who is right? (please indicate the correct one)

1. The revolution of the Earth around the Sun and the change of the Earth-Sun distance
2. The revolution of the Earth around the Sun and the inclination of the Earth's axis with respect to orbit's plane
3. The inclination of the Earth's axis with respect to the orbit's plane and its oscillation
4. The change of the Earth-Sun distance and the fact that the Earth axis is perpendicular to the orbit plane

State whether each of the following statements is true or false

Q13 Earth's motion around the Sun is a periodic motion on a closed orbit

Q14 Earth's orbit around the Sun is a very eccentric ellipse

Q15 Season periodicity is due to the revolution of the Earth around the Sun

Q16 Which of the following statements best explains the phenomenon of the different seasons? (please tick the correct one)

1. During the revolution, the distance between the Earth and the Sun changes so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface
2. During the revolution, the direction of the Earth's axis changes so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface
3. During the revolution, Earth's axis remains parallel to itself so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface
4. During revolution, Earth's axis is always perpendicular to the orbit plane so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface

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